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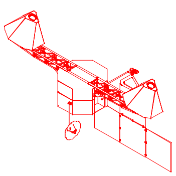

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Microdynamic Materials Properties of Composites for Space Applications

6th Biannual Microdynamics Workshop
NASA Jet Propulsion Lab, Pasadena, CA
23 June 1999

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Presentation Outline

- **Materials Properties for Macro Damping**
  - Typical algorithms and terminology
  - Composites vs. metals
  - Parameters influencing macrodynamic materials properties
- **Toward Microdynamic Materials Properties**
  - Typical materials and properties for space applications
  - Some empirical and anecdotal information
  - Optimizing microdynamic performance
  - Screening test matrix for space materials
- **Microcracking as an Input Energy**
  - Microcracking explained /criteria
  - Space composites performance
  - Proposed experiments

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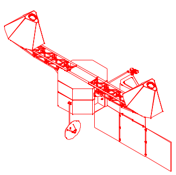

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Damping Terminology

Term	Symbol	Definition
% Critical Damping Factor	c_c	$c_c = 2\,m\,\omega_n = 2\sqrt{km}$
Viscous Damping (critical damping ratio)	ζ	$\zeta = \frac{c}{2m\omega_n} = \frac{c}{c_c}$
Structural Damping	g	$g = \eta = \frac{1}{Q} = 2\,\zeta$
Loss Factor (loss tangent, tanϕ)	η	$\eta = 2\,\zeta$ $\quad G^* = G\,(1 + i\,\eta)$
Quality Factor	Q	$Q = \frac{1}{\eta} = \frac{1}{2\zeta}$
Logarithmic Decay	δ	$\zeta = \frac{\delta}{2\pi}$ where $\delta = \ln\left(\frac{x_i}{x_{i+1}}\right)$
Specific Damping Capacity	Ψ	$\Psi = \frac{2\pi}{Q} = 2\pi\eta = 4\pi\xi$

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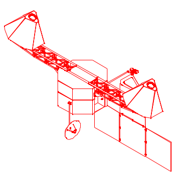

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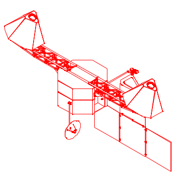
Composite Materials
Internal Damping Estimates

- **Probable Micro-Models for Damping**
  - Microplastic or viscoelastic phenomena associated with matrix
  - Relative slippage at the fiber-matrix interface
- **Given: Matrix damping capacity & fiber/matrix moduli:**
  - Can estimate internal damping of composite with known V_f
- **Typical levels for space structures**

  $\xi = 0.5$ to 2% critical

  - Optical benches are lowest, integral, in-plane designs



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Uni-Directional Lamina Damping Estimate

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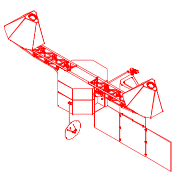

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Longitudinal Shear Specific Damping Capacity

$$\Psi_{LT} = \frac{\Psi_m (1-V_f)\left[(G+1)^2 + V_f (G-1)^2\right]}{\left[G(1+V_f)+1-V_f\right]\left[G(1-V_f)+1+V_f\right]}$$

Longitudinal Tension/Compression Specific Damping Capacity

$$\Psi_L = \Psi_m (1-V_f)\frac{E_m}{E_L}$$

Where, based on rule of mixtures

$$E_L = E_f V_f + E_m (1-V_f)$$

Transverse Specific Damping Capacity

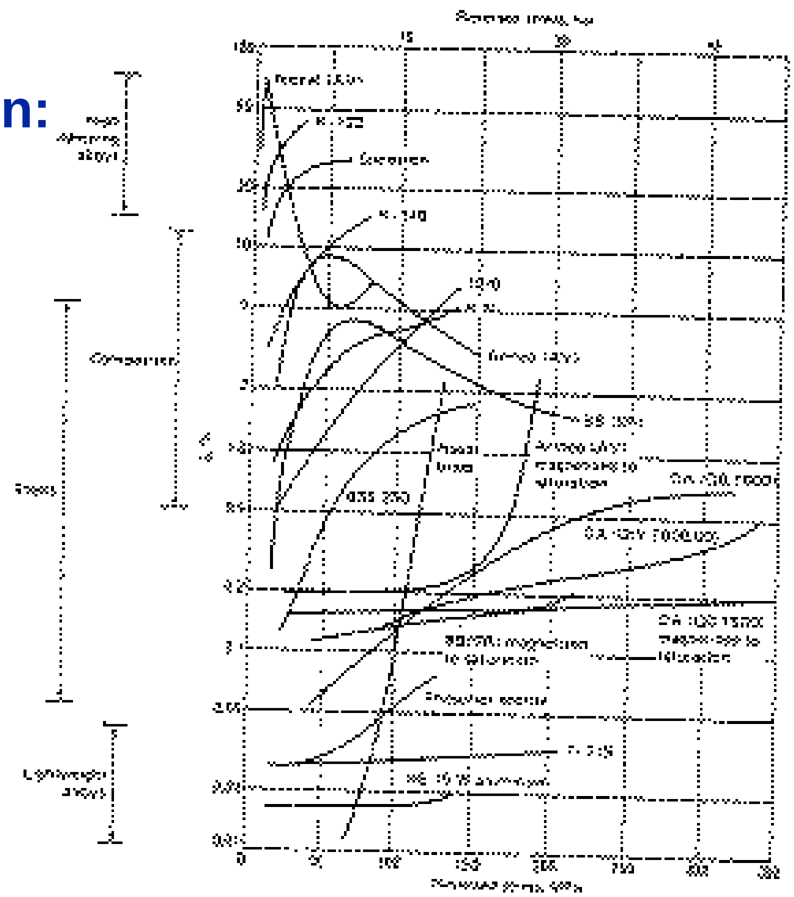
$$\Psi_T \quad \Psi_m$$

Laminate Damping Estimates	
Fiber Properties	
Name: T300	
Fiber Vol Fraction [%]:	55%
Fiber Longitudinal Modulus E_f [Msi]:	33
Fiber Shear Modulus G_f [Msi]:	3.2
Matrix Properties	
Name: 954-3	
Matrix Longitudinal Modulus E_m [Msi]:	0.4
Matrix Shear Modulus G_m [Msi]:	0.148
Matrix SDC Ψ_m [%]:	15.00%
(SDC: Specific Damping Capacity)	
Uni-Directional Lamina Damping Properties	
Shear Modulus Ratio G =	21.622
Longitudinal Young's Modulus E_L [Msi] =	18
(Based on rule of mixtures)	
Lamina Longitudinal Tension/Compression SDC Ψ_L [%] =	0.15%
Lamina Longitudinal Shear SDC Ψ_{LT} [%] =	13.14%
Lamina Transverse Tension/Compression SDC Ψ_T [%] =	9.84%
Longitudinal Tension/Compression	
Lamina Critical Damping ratio ζ [%] =	0.01%
Lamina Loss Factor η =	0.02%
Lamina Quality Factor Q =	4266
Longitudinal Shear	
Lamina Critical Damping ratio ζ [%] =	1.05%
Lamina Loss Factor η =	2.09%
Lamina Quality Factor Q =	48
Transverse Tension/Compression	
Lamina Critical Damping ratio ζ [%] =	0.78%
Lamina Loss Factor η =	1.57%
Lamina Quality Factor Q =	64

Ref : Adams, Robert D., “Damping Properties Analysis of Composites”, ASM International, Engineered Materials Handbook, Vol 1.

Composite Materials Damping

- **Composite material internal damping is highly dependent on:**
  - **Load levels (direct)**
  - **Loading frequency (direct)**
  - **Temperature (direct)**
  - **Composite Material:**
    - Moduli (extension, shear) (ind.)
    - Fiber volume fraction (ind.)
    - Ply orientation (thickness?)
  - **Fiber drives:**
    - Extensional moduli
  - **Resin drives:**
    - Shear and transverse moduli
    - Matrix damping capacity



Typical Composites for Space Structures

- By Structural Type
- Basic Requirements
- Typical Fiber and Resin Constituents

Structure Type	Requirements			Reinforcing Fibers		Matrix Resi
	Iso. Modulus (10E6 psi)	CTE (ppm/°C)	Outgas/CM	EPAN-based	Pitch-based	Type
1. Zero CTE Space	12 to 16	<±0.09	Very Low	M55J, M60J	P75, K135, K13710, XN50A	Cyanate
2. Stiff Structure	15 to 20	-3 to +4	NASA Spec	M55J, M60J	K135, XN50 K13710, K13C, P75	Epoxy or Cyanate
3. Aluminum Equivalent	>10	<23	NASA Spec	M40J, M46J	K63312	Epoxy
4. Fabric Skins / SAS	3 (Kev) to 40	±2	NASA Spec	M40J, M55J, M60J	XN50A, K13 K13C, XN70	Epoxy or Cyanate

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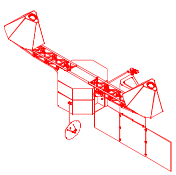

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Internal Damping Performance of Space Composites

- **Load levels**
  - Typically low (good)
- **Loading Frequencies**
  - Structural: first modes 4 to 150 Hz, ~low (bad)
  - Instrument: 100 to ? Hz for SIM, NGST, etc. (good?)
- **Composite Materials for Space**
  - High Stiffness: in-plane and on-axis (bad!)
  - Low Stiffness: transverse, shear moduli (good, but avoided)
  - Matrix Damping Capacity: epoxies, cyanates, VEMs (good)
  - Adhesives, Bonded Joints: continuous, but good damping

Laminate Damping Variation w/ Ply Angle

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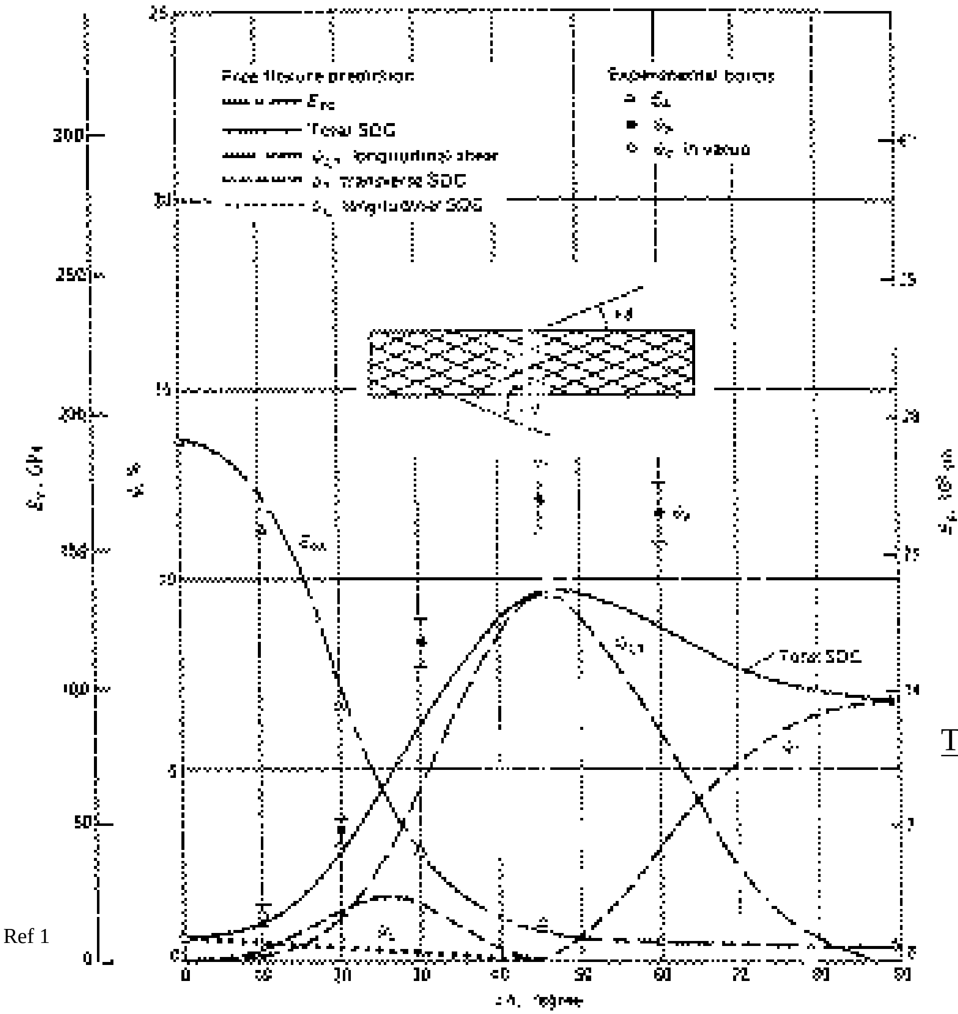

$$\Psi_\vartheta = \frac{1}{s_{11}}\left(\frac{\Psi_T}{E_T}\sin^4\vartheta + \frac{\Psi_{LT}}{G_{LT}}\sin^2\vartheta\cos^2\vartheta\right)$$

Bias Plies +/- 45deg:

chart ? Ψ 10%

$$? \ \zeta = \frac{\Psi}{4\pi} = 0.008 \ or \ 0.8\%$$

T300/954-3 [0/45/90/135] Laminate:

$? \ \zeta \quad 0.01 \ or \ 1.0\%$

T300/IM8 Hybrid [0_n/+45/-45/0_n/...] Laminate:

$? \ \zeta \quad 0.006 \ or \ 0.6\%$

Ref : Adams, Robert D., “Damping Properties Analysis of Composites”, ASM International, Engineered Materials Handbook, Vol 1.

Empirical Info on Composites Damping

- **Pitch versus PAN**
  - Several sporting goods references cite much better damping from pitch-based than PAN-based fibers of the same moduli
  - Could be related to higher micro-strain levels in matrices around pitch fibers or to a difference in fiber damping capacity
- **Interlayers Work**
  - Numerous references (AFRL SPICE program, others) have shown visco-elastic materials (VEMs) like poyurethanes, silicones do increase damping without hampering structural performance
- **Use Materials With Hysterisis**
  - Early non-linearity in shear responses
  - VEMs which can be engineered within the glass transition zone

Improving Space Composite Damping

- **Extensional Moduli**
  - Use highly-off axis laminates
  - Consider lower modulus fibers (Carbon, Glass, Kevlar)
  - Design ‘soft’ boundaries / interfaces where possible
- **Shear and Transverse Moduli**
  - Use lower modulus resins (e.g. cyanate vs. epoxy)
- **Matrix Damping Capacity**
  - Choose resins with ‘early’ non-linear shear responses
  - Use interlaminar VEMs, or resin rich layers
  - Load resins with low E or high damping phases
- **Other**
  - Choose fibers with higher damping (pitch vs. PAN ?)
  - Use smaller ply thicknesses (more discreet interlaminar layers)

Screening Matrix for Microdynamic Properties of Space Composites

- **Parametric Test Matrix**
- **Choose Parameters and # of Settings**
  - Based on available budgets

Test Types	**Test Conditions**		**Materials**	
	Type, Settings	**Temps.**	**Fibers**	**Resins**
Damping Ratio	High & Low on Freq. & Amp.	77 K, 300 K	M55J (78), K13710 (90), T300 (33), K1100 (140), Kevlar	Cyanate, Epoxy, Modifieds, VEM layers
Extensional Modulus	Uni TN or CM			
Shear Modulus	±45 TN, Iosipescu			
Transverse Modulus	90° TN or CM, FWT			
Fiber Volume	50% & 60%			

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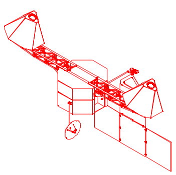

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Microcracking in Space Composites

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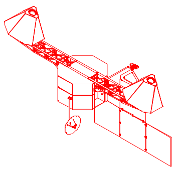

Space Interferometry Mission

- **Will Probably Happen Due To:**
  - Temps below about -100°C
  - Zero CTE laminates have highly negative CTE fibers
  - Ply thicknesses typically 2.5 to 5 mils (64 to 127 microns)
  - Current resin properties: cyanates are better, but not that good.
- **Mitigating Techniques**
  - Layup orientations with gradual transition
    - I.e. (0,45,90, 135)XS better than (0, 90, +45, -45)XS
  - Thinner plies
    - 25 micron possible, but expensive and limits fiber choices
  - Higher strain matrices
    - Elastomer loading, high strain base resins
    - VEMs like polyurethane as interlaminar layers

Microcracking Micromechanics

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Space Interferometry Mission

- Negative CTE of neighboring plies adds to tensile thermal stress in resin on cool down until resin fails

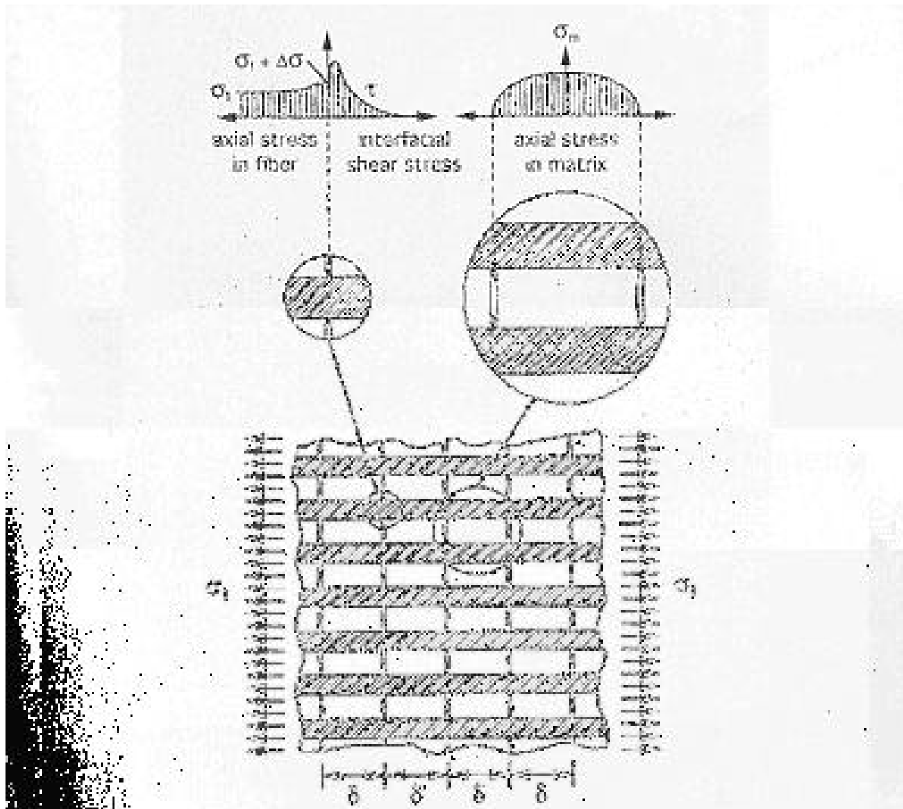

Fig. 4.7 Matrix cracking and local stress distributions in unidirectional brittle matrix composite under longitudinal tension.

Ref : Daniel, Isaac M. and Ishai, Ori, “Engineering Mechanics of Composite Materials,” p.93

Microcracking Damage Progression

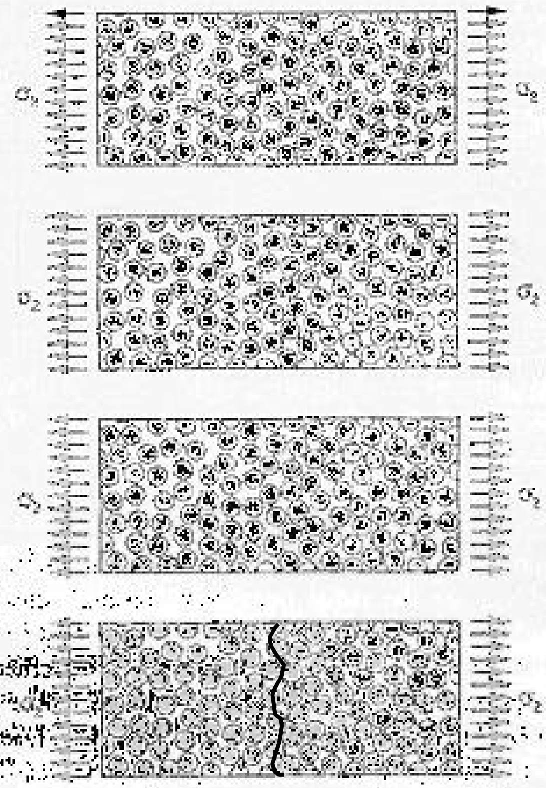

Fig. 4.17 Progressive microcracking leading to ultimate failure in unidirectional composite under transverse tension.

Ref : Daniel, Isaac M. and Ishai, Ori, “Engineering Mechanics of Composite Materials,” p. 100

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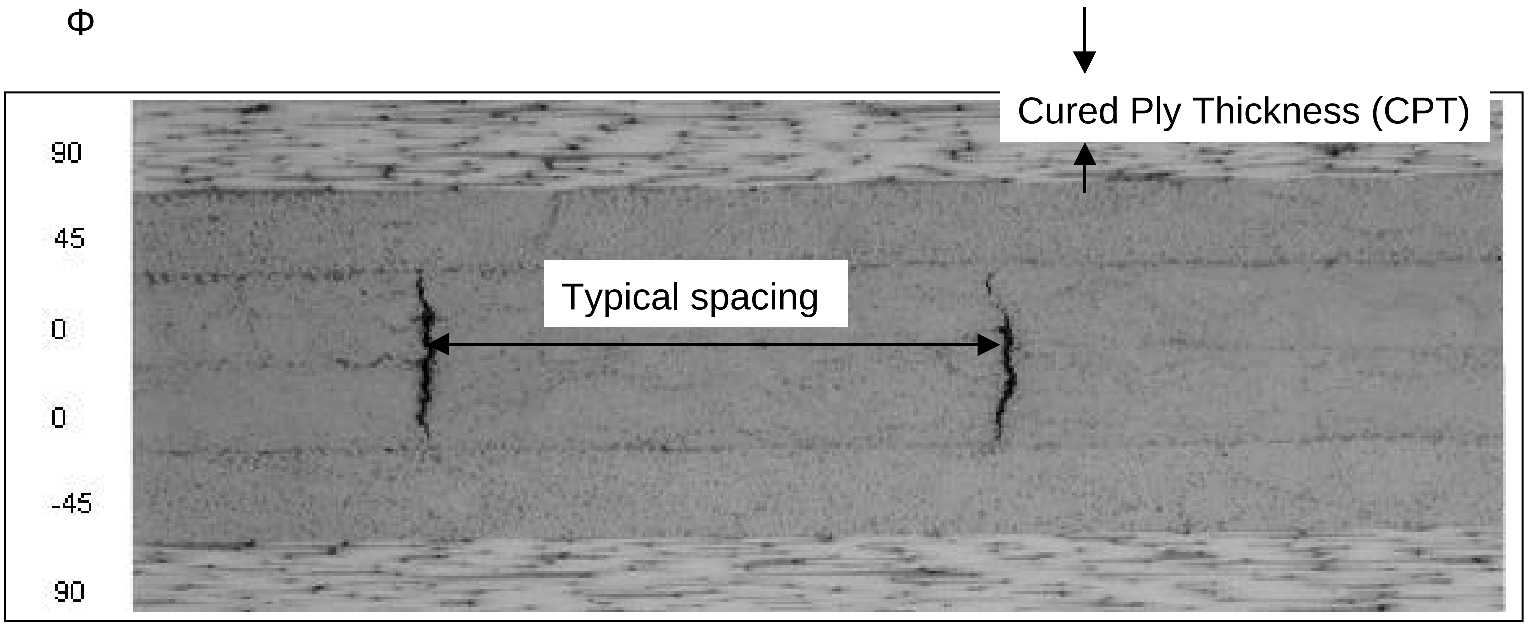
Microcracking in a Space Composite

Ply Orientation Φ



Resin Type / Ultimate Strain ($\varepsilon^{ULT}_{RESIN}$

Coefficient of Thermal Expansion (CTE) of the fiber (α_{FIBER})

Fiber Volume Fraction (FV)

Typical spacing between cracks = $f(\varepsilon^{ULT}_{RESIN}, \alpha_{FIBER}, FV, \Phi, CPT)$

Material: M55J / 934

Ply Thickness: 4.5 mils (114 microns)

Fiber Volume Fraction: 59%

Microcracking Performance of Space Composites

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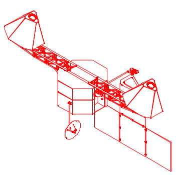

Space Interferometry Mission

Resin System	Ply Thickness (MILS)	Cracks/Inch (After No. of Cycles)			
		0 Cycles	10 Cycles	50 Cycles	100 Cycles
934	5.0	3.0	33.0	53.5	56.0
954-3	5.0	0.5	4.0	6.5	10.0
934	2.5	0	2.0	2.5	3.0
954-3	2.5	0	0	0	0

Notes:

1. P-75 laminates, $(45, 0, -45, 90)_{3S}$, 60% FV, 2 in. x 2 in.
2. Cycle: -- 150° F to +150 ° F and back @ 20° F/min., 5 min. dwell at extremes.
3. Data taken at 50x magnification; values are average of 0 ° normal and 90 ° normal edges.

Proposed Microcracking Experiments

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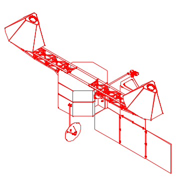

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- **Create Laminates Which Will Microcrack**
  - M55J, (0,90)XS or (0,45,90,135)XS
  - Cyanate and epoxy resins
- **Monitor During Thermal Cycles (to 196 K, ~ 20 cycles)**
  - CU Microdynamics Lab, or
  - Adapt COI Liquid Helium CTE facility
  - Acoustic emission measured
  - Dynamic response measured
- **Characterize:**
  - Frequencies
  - Energy, amplitude
  - Internal composite damping for microcracking input